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Massive Solar-Thermal Collectors: A critical literature review

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ABSTRACT

The present work reviews the literature produced so far on high-capacitance solar thermal collectors, with the aim of highlighting the wide range of possible variants and applications and sharing the information here gathered for future developments. These solar systems are here denoted with the term of Massive Solar-Thermal Collector (MSTC). The review is focused on liquid rather air technologies, because of their direct applicability to systems that supply only domestic hot water (DHW) as well as combined DHW and space heating (SH) systems. The attention on this topic is justified by the rising number of publications and energy concepts that deal with the utilization of opaque structures as low cost solar absorbers and by the similar MSTC's efficiency in low temperature range to conventional solar systems.

Contents

1. An introduction to Massive Solar-Thermal Collectors

The growth in the use of solar collectors for covering building loads (domestic hot water (DHW) preparation and space heating (SH), mainly) has shown that these systems are mature and technically reliable. Research and development of solar technologies has led to very efficient solar collectors and systems. A greater share of solar energy in residential building loads can become more significant thanks to thermally well-insulated buildings and the adoption of low temperature heat supply systems. Among technical aspects, solar technologies are also essential measures in order to comply with more and more severe building's energy requirements in terms of primary energy or CO_2 emissions reduction.

The most diffuse solar technologies are flat-plate solar collectors (FPC) and a wide range of typologies [1–5] and materials [6–8] are available on the market. From an economical point of view, traditional solar collectors are characterized by high cost of investment and this is a weighty limit in spreading further their adoption in residential applications [9,10]. Their high cost is mainly due to the use of expensive materials and to the required accurate

Abbreviations: CCC, cellular-clayey concrete; COP, coefficient of performance; DHW, domestic hot water; FDM, finite difference method; FEM, finite element method; FVM, finite volume method; FPC, flat-plate collector; GRC, glass-reinforced concrete; HWB, Hottel-Whillier-Bliss theory; IEI, initial energy investment [kWh]; LCM, lumped capacity method; MSTC, massive solar-thermal collector; RCC, reinforced cement concrete; RFM, response factor method; SAHP, solar assisted heat pump; SCOP, seasonal coefficient of performance; SF, solar fraction [%]; SFH, single family house; SH, space heating; SHDHW, space heating and domestic hot water; SPHS, swimming pool heating system; SPF, seasonal performance factor.

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Nomenclature

a	diffusivity [m^2/s]
a_0, a_1, a_2	collector efficiency coefficients [–], [W/(m^2 K)], [W/(m^2 K^2)]
A_c	collector area [m^2]
Bi	Biot Number
c_p	specific heat [kJ/(kg K)]
C	volumetric thermal capacity [kJ/(m^3 K)]
C_{eff}	effective thermal capacity [kJ/(m^3 K)]
d	thickness [m]
d_1	depth of piping grid [m]
d_g	air gap [m]
d_x	pipe spacing [m]
Fo	Fourier Number
F_R	heat removal factor
F'	collector efficiency factor
I_g	global solar radiation [W/m^2]
$\dot{m}$	mass flow rate [kg/h]
p_v	vapour pressure [Pa]
q_u	specific heat flux [W/m^2]
Q_u	heat flux [W]
s_d	equivalent layer thickness [m]
S_d	total equivalent element thickness [m]
t	time [s]
T	temperature [K]
T_S	heat removal temperature [K]
U	U-value [W/(m^2 K)]
U_0	heat transfer coefficient between fluid and ambient air [W/(m^2 K)]
U_L	thermal loss coefficient [W/(m^2 K)]
w	water uptake coefficient [kg/(m^2 h$^{0.5}$)]

Greek letters

α	absorptance
δ	pipe diameter [m]
η	energy efficiency
λ	thermal conductivity [W/mK]
μ	permeability
ρ	density [kg/m^3]

Subscripts

air	ambient temperature
av	average
conv	convective
d	daily
e	external
eff	effective
f	fluid
i	internal
sa	sol–air
sat	saturation
sp	specific
tot	total

manufacturing phases: thus, large cost reductions are needed in solar SH and DHW systems to achieve a significant penetration in the residential market.

Two general approaches can be indicated as effective strategies to reduce the economic impact of solar thermal collectors. A first trend goes in the direction of manufacturing low-cost collectors with the adoption of alternative materials (e.g. non-metallic, plastic, fibre-glass or rubber) [8,10,11], which represent valid options to traditional materials in low temperature range (delivered fluid temperature < 50 °C). A second trend goes in the direction of a better integration of solar systems in building envelope [12] and deals with a more integrated design between formal and technical aspects.

The ideal absorber material would be "inexpensive, easy to form, strong (in terms of pressure and handling), stable at temperature of 205 °C, stable under long-term exposure to ultraviolet radiation, nonporous, lightweight and completely noncorrosive" [11]. Unlikely a material cannot meet all these criteria and a compromise has to be found among all these requirements and thus additional research should be addressed in this direction.

A more effective integration of solar collection systems with the building envelope is always desirable [12–16]. Typically solar collectors are considered mere technical elements and they are installed on the roof top where the visual impact is less prominent. The integration of solar systems is affected by the "linear" design approach, in which architects deal with aesthetic and functional issues, while engineers are responsible of mere energy aspects. The consequence of this is that the degree of freedom of integrating solar thermal systems is restricted already in early design phases. A more effective collaboration between stakeholders, moving toward an integrated design approach, will improve the formal and technical quality of the building and reduce investment and maintenance costs.

In order to achieve these results from technical and aesthetic point of view, a greater design effort is necessary [12–16]. In the last decades, a technological trend has been established, which moves toward a multi-functional façade concept, in which bearing, water-proofing, sound protection, insulation and surface finishing are solved. As further improvement to this, pre-manufactured modular building elements can be also equipped by means of solar energy collection and help to fulfil DHW and heating loads. These techniques can be adopted successfully either for residential and tertiary buildings.

A significant example of possible integration of solar energy technologies in building elements, are represented by Massive Solar-Thermal Collectors (MSTCs). With this term, the authors refer to those massive structures, which are exposed outdoors and serve as active solar systems for a direct or indirect use of the collected energy in covering the building loads. MSCs have been studied since the late 70 s as reaction to the oil crisis, but no widely commercial applications have been developed so far. Evidences of their working effectiveness are limited to relative few literature references and a moderate concern has been testified through the number of patents registered. MSTCs adopt as absorber a massive material (typically concrete) instead of the metallic one and basically, they use similar techniques of floor heating systems to external vertical or horizontal structures. The working fluid is usually water or a brine–water mixture, which flows through the pipes embedded in collector's absorber. Pipe's material can be metallic (such as aluminium or copper) or plastic (PE, PE-X or HDPE). The glazing layer is adopted in order to enhance collector's efficiency by reducing the heat loss coefficient, but in some cases it is neglected because of the fragility and the high investment cost of the glass. As previously said, only few commercial systems have been developed and in order to show the whole range of possibilities, a summary of the most interesting technologies is presented in the following sections.

One of the most significant advantages of MSTCs is their thermal capacity, that induces a storage effect of solar energy and makes possible to extract heat also during periods with no availability of solar radiation. The non-negligible thermal inertia, and in some cases the lack of glass panes, changes radically the behaviour with respect to a conventional FPC. In general, the major advantages of using a MSTC can be summarized as follows:

- it has a structural integrity to withstand external loads and thus can be used in many external applications and structures;
- it can become a free radiant surface, connectable to a plurality of other units;
- traditional concrete precast techniques can be adopted to create a modular system, which can be produced locally from local materials;
- a MSTC prototype can be easily constructed, guarantying high quality standards;
- it has lower investment costs and it is easy to maintain and to operate;
- the concrete structure eliminates the need of a collector frame.

The system applications in which MSTCs can be implemented are wide (see Section 4, Tables 1 and 2). They have been adopted for covering the energy demand of residential buildings (SH and DHW) and swimming pools, for reducing the solar gains on opaque elements or for lowering the pavement temperature reducing the local heat island effect. Nevertheless, it has to be underlined that whenever approaching to the adoption of any solar technology, it is important to understand the local availability of the energy source and its compatibility with the requirements and peculiarities of the building loads. This statement is particular true for any MSTC system.

In order to address more effectively the work, a critical analysis of MSTC examples available in literature are reported in the next sections. The aim of the authors is to show the wide range of possible applications and the major thermo-physical and technological characteristics of a MSTC, sharing the information here gathered for future developments.

2. Thermal and hygrometric analysis of a MSTC

In order to guarantee adequate durability and stability levels, thermo-physical and technological aspects are together the most important issues to consider thoughtfully when manufacturing a MSTC. Relevant aspects on heat transfer and storing, vapour diffusion and frost deposit are addressed in the next sections.

2.1. Heat transfer and storing phenomena

The most evident difference of a MSTC from traditional FPCs, is the thermal behaviour of absorber. In general, massive materials have a lower thermal conductivity than metals, but a greater heat storing effect. The final energy response of MSTCs depends on these issues and thus, these aspects need to be clearly discussed.

As shown by Fourier's law (Eq. (1)), the heat conduction rate is directly dependent to the thermal diffusivity of a material ($a = \lambda/\rho c$): substances with high thermal diffusivity rapidly adjust their temperature to that of their surroundings, because they conduct heat quickly in comparison to their volumetric heat capacity.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\nabla^2 T \tag{1}$$

In the case of opaque materials, it is possible to derive a direct correlation between the density ρ and the thermal conductivity λ (Fig. 1). Light materials have a larger quantity of porous, while heavy substances have a less number of voids. This distinction determines their different field of applications. Massive materials are mainly applied for static requirements, such as brick in masonries or concrete for casting beams. The density ranges between 400 and 2800 kg/m^3 and their bearing ability increases when cavities or leakages are limited, while the thermal conductivity is generally higher than 1.0 W/mK. On the other hand, light weighted materials are applied for insulation purposes, because of the amount of air entertained is a measure of the material's insulating ability. In this case, the density can vary between 25 and 270 kg/m^3 and their thermal conductivity between 0.020 and 0.050 W/(m K).

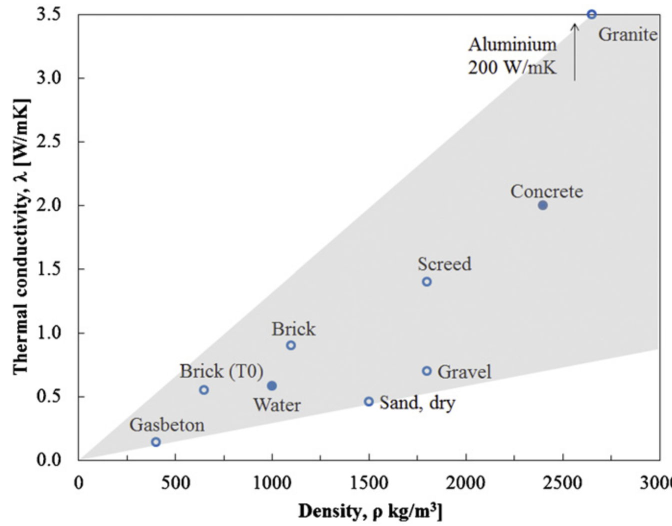

Fig. 1. Thermal conductivity λ as a function of density ρ for some common building materials [17,18].

The specific heat capacity c_p does not differ significantly from one building material (heavy or light) to another and it is usually around 1.0 kJ/(kg K) (except wood where $c_p \approx 2.0$ kJ/(kg K)). An ideal material used in active or passive solar systems should have an high specific heat, in order to store the highest fraction of solar radiation, but also an high thermal conductivity in order to transfer the stored heat to further processes. Thus, massive materials have an important potential of collecting solar energy, because of their relative high thermal conductivity and high heat capacity. In order to understand and compare correctly the storage capacity of several materials, a more appropriate parameter to use is the volumetric heat capacity $C = \rho c_p$. Looking at Fig. 2, it can be deduced that with a volumetric heat capacity of 0.66 kWh/(m^3 K), concrete reaches about 60% of water (the highest value). This means that from a thermal point of view concrete is a valuable material for solar applications in which energy storing is an issue. For sake of completeness, it has to be reported that several works [19–23] proposed the combination of concrete with PCM materials in order to

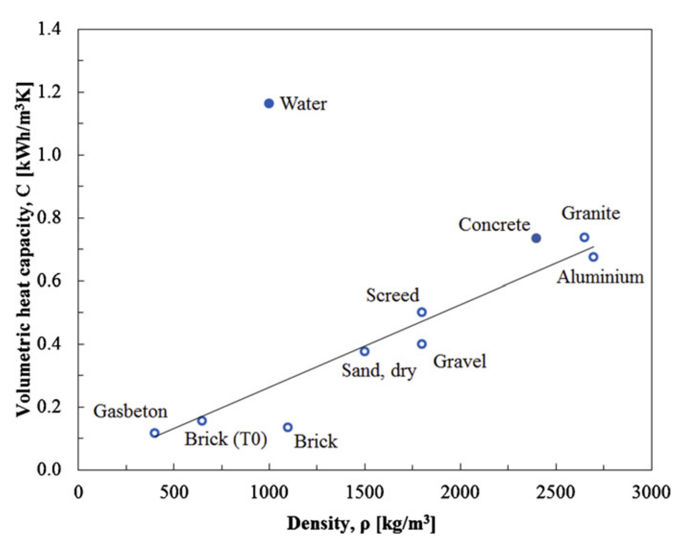

Fig. 2. Heat capacity C as function of density ρ for some common building materials [17,18].

Table 1
Synoptic table of the reviewed Massive Solar Collector typologies part 1 (T = theoretical, E = experimental, W = water heating, H = space heating, C = cooling, DI = de-icing, P = pool heating, D = direct, I = indirect).

Author	Year	Location	Analysis [T/E]	Classification	Application	Exploitation	Tilt angle [°]	a_0 [–]	a_1 [W/(m^2 K)]	a_2 [W/(m^2 K^2)]	U_c [W/(m^2 K)]	η_d [%]
Olive (1)	1977	France	E	2	W	D	–	0.86	4.13	–	4.8	–
Olive (2)	1977	France	E	2	W	D	60	0.87	3.13	–	3.6	–
Olive (3)	1977	France	E	2	W	D	40	0.83	5.47	–	6.6	–
Sodha	1980	India	T	1	W	D	45	–	–	–	6.1	30–58
Sedgwich	1981	U.K.	T	1	P	D	0	–	–	–	–	–
Kumar	1981	India	T	3	C	D	0	–	–	–	4.8	28–35
Srivastava	1982	India	T	1	W	D	0	–	–	–	4.8	25–50
Turner	1986, 1987	U.S.	T	1	P	D	0	–	–	–	14.2	–
Kutscher (1)	1984	U.S.	T/E	2	W	D	–	–	–	–	–	–
Kutscher (2)	1984	U.S.	T/E	2	W	D	–	–	–	–	–	–
Oswald	1984	Germany	E	3	W/H	I	35	–	–	–	–	–
Nayak	1989	India	E	2	W	D	19	0.52–0.37	0.18–0.24	–	–	12.8–70.3
Bosphetty	1992	India	T	2	W	D	19	0.52–0.37	0.18–0.24	–	–	17.1–56.7
Sokolov	1992	Israel	T	2	W	D	–	–	–	–	2–20	41–86
Al-Saad (1)	1993	Jordan	E	2	W	D	32	0.453–0.754	2.36–4.60	–	–	40.0–50.4
Al-Saad (2)	1993	Jordan	E	2	W	D	32	0.303–0.620	1.13–2.98	–	–	33.1–43.0
Al-Saad (3)	1993	Jordan	E	2	W	D	32	0.350–0.715	2.13–4.28	–	–	36.0–48.0
Marmoret	2000	France	T/E	3	H	D	90	–	–	–	–	–
Chaurasia	2000	India	E	2	W	D	0, 41, 90	–	–	–	–	–
Rocchetti	2001, 2011	Italy	T	3	W	I	15	–	–	–	–	–
Abbott	2004	U.S.	T	3	W/H	I	33, 41	–	–	–	–	42
Hazami	2010	Tunisia	T/E	2	W	D	37	–	–	–	14	32
Gao	2010	China	T	1	DI	D	0	–	–	–	36	21–42
Wu	2011	China	E	1	DI	D	0	–	–	–	–	33
Sarachitti	2011	India	T/E	3	W	D	0	–	–	–	30	–
Ruschenburg	2011	Germany	T/E	3	H	I	90	–	–	–	–	–

Table 2
Synoptic table of the reviewed Massive Solar Collector typologies (part 2).

Author	A [m^2]	t [mm]	Massive material	λ [W/(m K)]	ρ [kg/m^3]	c [kJ/kg K]	Pipe material	d_x [mm]	δ [mm]	t_1 [mm]	$\dot{m}_f$		Fluid	Glazing [yes/no]	t_g [mm]
											[kg/h]	[kg/h/m^2]			
Olive (1)	–	150	Concrete	–	–	–	Steel	150	21	–	–	–	Water	Yes	–
Olive (2)	–	80	Concrete	–	–	–	Plastic	80	17	–	–	–	Water	Yes	–
Olive (3)	–	80	Concrete	–	–	–	Steel	150	21	–	–	–	Water	Yes	–
Sodha	0.74	50	Sand	1.73	2243	0.88	PE		7	20	28	–	Water	Yes	40
Sedgwich	560	–	Asphalt	1.18	–	–	PE	125	9.5	–	–	–	Water	No	–
Kumar	–	300	Concrete	0.72	1858	0.66	–	–	10	0–300	–	2.5–20	Water	Yes	–
Srivastava	–	300	Concrete	0.72	1858	0.66	–	–	10	0–300	0–20	–	Water	Yes	–
Turner	–	100	Concrete	–	–	–	–	125	–	–	–	–	Water	No	–
Kutscher (1)	2.00	–	GRC	–	1400	–	None	30–90	10	–	–	–	Water	Yes	–
Kutscher (2)	2.00	–	GRC	–	1400	–	None	30–90	10	–	–	–	Water	No	–
Oswald	115	160	Concrete	–	–	–	PE	–	–	–	–	–	Brine	No	–
Nayak	0.90	35	Cellular concrete	0.92	2262	0.84	PVC	60–150	20	18	36–72	–	Water	Yes	40
Bosphetty	0.90	35	Cellular concrete	0.92	2262	0.84	PVC	60–150	20	18	36–72	–	Water	Yes	40
Sokolov	–	20	GRC	1.00	2400	0.85	–	40–100	10	–	–	18–72	Water	No	–
Al-Saad (1)	0.90	50	Concrete	–	–	–	Steel	–	16	–	–	39.6–118.8	Water	Yes	40
Al-Saad (2)	0.90	50	Concrete	–	–	–	PE	–	13	–	–	39.6–118.8	Water	Yes	40
Al-Saad (3)	0.93	50	Concrete	–	–	–	PVC	–	14	–	–	39.6–118.8	Water	Yes	40
Marmoret	1.88	200	CCC	0.20	850	0.85	–	–	–	–	336–540	–	Water	No	–
Chaurasia	1.07	55	RCC	–	–	–	Aluminium	60	19	0	80–100	–	Water	No	–
Rocchetti	150	15	Concrete	1.49	–	–	PE-X	60	–	–	–	–	Brine	No	–
Abbott	28.6	38	Concrete	0.6	840	1.60	PE	20	19	–	155	–	Brine	Yes	25
Hazami	2.00	40	Concrete	0.81	–	0.88	Copper	100	14	–	149.76	–	Water	Yes	20
Gao	0.72	–	Asphalt	–	–	–	–	90–150	20	–	70–100	–	Water	No	–
Wu	0.09	150	Asphalt	1.73, 1.89	–	–	Copper	100	20	75	0–120	–	Water	No	–
Sarachitti	5.75	120	RCC	1.40	2300	0.88	PVC	100	25	50	–	–	Water	No	–
Ruschenburg	2.5–5	–	Plaster	–	–	–	PE	–	–	–	–	–	Brine	No	–

further enhance its thermal storage capacity: this issue has not been handled in this work.

Accordingly to the solar technology adopted and the integration level in building façade, solar energy collection is always associated with heat removals of different magnitude. In liquid systems, water or glycol mixture is used to extract heat from the absorber plate through convection. If a concrete collector is simply installed on a roof surface, the roof structure is not thermally affected by its presence. On the other hand, if a MSTC is integrated in building envelope, it causes a change in building heat losses due to thermal transmission and thus occupants' comfort issues should be carefully considered. For sake of clarity, a steady state calculation, reported in [24], gives an outlook of the abovementioned phenomena. Here an external wall made of 14 cm of concrete, 6 cm of insulation and 4 cm of concrete from inside to outside is considered. The assembly has a U-value of 0.50 W/(m^2 K) and it implements a pipe coil on the external concrete layer. Assuming winter boundary conditions (indoor: +20 °C, outdoor: −10 °C and no solar gains), the net lost energy flux amounts to 15.1 W/m^2. If a constant flux of 100 W/m^2 is removed, the energy lost from indoor to outdoor rises to 18.1 W/m^2. Thus, it can be concluded that the greater the degree of integration of solar technologies in building envelope and the colder the weather location, the more important precautions should be taken in order to minimize undesired drawbacks. During the summer season, the heat removal from building envelope could become an effective strategy for reducing the cooling demand [25]. This is particularly true for hot or arid climates, because the heat removal implies a reduction of the indoor radiant temperature and so an improvement of the comfort level. The collected heat can be easily used for preheating or producing DHW (see Section 4).

As said, heat storing is a further central aspect in MSTCs. Bilgen [26] studied experimentally the transient thermal behaviour of a concrete slab by varying the incident radiant heat flux. As we can expect, the absorbed heat flux decreased with time independently from the incident heat flux. This means that the capacity in heat storing is "limited" and the material becomes "saturated" when a thermal equilibrium state is reached between radiant heat gains and losses. If suddenly the radiant heat flux is removed, the discharge phase appeared more intense than the charge accordingly to a non-linear trend of time. Furthermore, he investigated the effect of concrete slab thickness (varied from 80 mm to 200 mm) on storing efficiency, which has been defined as the ratio between the change in stored heat and the incident radiant flux. Bilgen noted that by doubling the concrete thickness, the energy storing efficiency increased by 30%; this tendency is not linear and the most significant changes are shown for moderate thick slabs of about 12 cm. These results were confirmed theoretically by Cossali [27,28], which investigated the same topic, describing formally the dynamic storage capacity of concrete slabs. He put in evidence as an optimal slab exists that maximizes the heat storage capacity accordingly to the intensity and duration of the heating profile (solar gains) adopted.

The notion of volumetric thermal capacity is a useful parameter to quantify the storage capacity of different materials. As reported in [29], the effective thermal capacitance C_{eff} is a collector's parameter which gives information regarding its transient behaviour. In the case of solar collectors with a non-negligible thermal mass, it is preferable to use the notion of effective thermal capacity C_{eff} rather than the volumetric capacity C, because it gives a better understanding of the maximum heat amount that could be stored under transient environmental conditions.

2.2. Moisture transfer phenomena

The integration of active technologies in building envelope has not only effects on thermal aspects. As widely-known, vapour saturation pressure and hygroscopic properties (e.g. μ-value) of a porous material are temperature functions. Moreover, the pores in an opaque material can contain air, liquid water, water vapour or ice and the presence of one of these is dependent to the local temperature. Typically, the presence of water in a structure can be determined by several causes such as superficial or interstitial condensation, raising ground moisture, driving rain or by the initial water content, while the transfer mechanisms are diffusion and capillarity. An uncontrolled moisture content can lead directly or indirectly to structural damages or affect the durability of element.

A dedicated study [24] dealt with investigations on this issue, discussing the influence and the magnitude of the moisture content on the durability and the energy collection of vertical MSTC integrated in building envelope. Under "undisturbed" conditions, the assembly above described is characterized by a vapour flow rate diffusion of 3.3×10^{-5} kg/h/m^2 and the condensed water vapour amounts to 0.047 kg/m^2. When extracting an heat flux of 100 W/m^2, internal temperatures drop down, increasing the risk of interstitial condensation. Under these conditions vapour flow rate increases up to 3.7×10^{-5} kg/h/m^2, as well as condensed water (0.053 kg/m^2). It should be pointed out that this calculation is performed under steady state conditions, neglecting the potential evaporation of the interstitial condensed water. Moreover in [24], field tests showed that no significant differences in moisture content within MSTC's core structure or in the surroundings of wall pipe occurred. The measured water content amounted to 6% of MSTC's weight, which corresponds to a quantity 1% higher of the ordinary value of exposed concrete elements. The authors did not notice any damages caused by frost deposit during test periods in winter season.

In order to understand the relationship between evaporation and heat release from a massive structure, the work of [30] is helpful. This specific issue has been studied on a cellular clayey concrete element, which embedded a pipe network. Two series of thermocouples and a hygrometer were used to measure the heat transfer and the water content at a given depth of the element. The measurements showed how temperature variations affect the saturating vapour pressure $p_{\mathrm{v,sat}}$. The calculation testified that the effect of evaporation on the heat transfer is negligible, but its effect is significant on the gradient of mass transfer.

Finally, the work of [24] suggested a list of measures in order to satisfy durability issues against moisture transfer in a MSTC. Firstly, it is important to avoid an increase of moisture content, by limiting undesired operation conditions. If this would not be possible, design efforts should be directed towards to restrain water capillarity, limiting the porosity of massive material, to facilitate moisture diffusion by choosing a low-vapour resistance structure (low S_{d} value) and to allow the release of vapour in surrounding environment. In order to do that, the MSTC external surface should be coated with a plaster layer of specific characteristics ($w \leq 0.5$ kg/(m^2 h$^{0.5}$), $s_{\mathrm{d}} \leq 4$ m and $(w{\cdot}s_{\mathrm{d}}) \leq 0.3$ kg/(m h$^{0.5}$)). Secondly, a low initial water content should be guaranteed through an effective maturing phase of concrete. Finally, in order to reduce possible damages due to icing and thawing cycles, longer periods below zero of the structure should be avoided.

2.3. Frost protection

Problems associated to frost formation in a MSTC are determined to intense heat removal and can occur on external surfaces as well as interstitially. These issues affect the durability [31], but also the energy performance. In particular when surface condensation occurs, the liquid water depositing can become solid (frost or ice), if particular cold ambient temperatures occur. The creation of a frost layer increases the thermal resistance and thus, reduces the heat gain from the environment.

Two main frost durability problems can be recognized for concrete: internal cracking due to freezing and thawing cycles, and surface scaling [32,33]. The first issue is a well-studied problem. Internal cracks due to freezing can be tackled ensuring an adequate system of entrained air voids. Field and laboratory tests confirm, that a critical void spacing exists, beyond which the protection against unfavourable effects is no longer guaranteed. This minimum spacing is 200 μm and it is a reliable value for almost all types of concretes also under very low temperatures (−20 °C). Scaling is a progressive deterioration of external layers that leads to a detachment of superficial mortar or cement paste. This phenomenon is still today not perfectly understood, but in general it is due to differential pressures under concrete surface caused by the presence of salts in cement paste. In order to tackle this problem, an accurate control on air entrainment and water/binder ratio could be an effective measure. When the concrete porosity cannot be increased because of the consequent strength reduction, it is possible to influence the air-entrainment degree by chilling the aggregates mixture. This operation requires accurate environmental conditions that can be affordable only in manufacturing plant.

These good-practices are evidenced in the reality. Pigeon [33] shows some results of some monitoring tests. He noted that whenever small frost deposits on external surfaces occur, the MSTC efficiency is not affected significantly, but if frost layers become thicker, their influence cannot longer be neglected. These critical conditions occurs only when MSTC is intensively damped (e.g. capillary water, rain, air humidity) and here particular care should be given.

These recommendations put in evidence that an upper limit of concrete density exists, with the consequence of reducing the energy response, in order to guarantee satisfactory durability levels. However, this is true only for such climatic contexts where severe winter conditions occur and for applications in which MSTC could operate below zero temperature (such as an heat pump coupling). Nevertheless due to the unusual application, the number of works which have dealt with medium-term monitoring of MSTC systems is limited. This would be an important research branch on which more detailed investigations and measurements on field should be carried out.

3. Numerical methods

A discussed aspect in modelling a MSTC has been the heat conduction through the massive matrix under time-varying boundary conditions and in the following, particular attention will be given to this issue. For sake of clarity, this section does not aim to discuss exhaustively numerical methods for calculating heat transfer in opaque elements, but only to comment the techniques applied in the reviewed works.

The heat transfer in MSTC systems is a coupled conduction, convection and radiation problem, with appropriate boundary conditions. The incident solar radiation I_g can be transmitted, reflected and absorbed, accordingly to optical properties of external surfaces. The absorbed fraction is partially transferred by conduction through the solid material until pipe wall and then removed by convection through the working fluid. The collector heat losses are expressed with the parameter U_L, which is a function of convective and long-wave radiative heat transfer coefficient between the absorber plate, glass cover (if present) and ambient. Typically this value is not a constant, but for unglazed collectors it can be assumed so [34]. Accordingly to the degree of integration in building envelope (see Section 4), boundary conditions acting on the bottom surface of a MSTC can be of the first kind (when the contact surface temperature is known) or of the second and third kind (convective and radiative heat flux known).

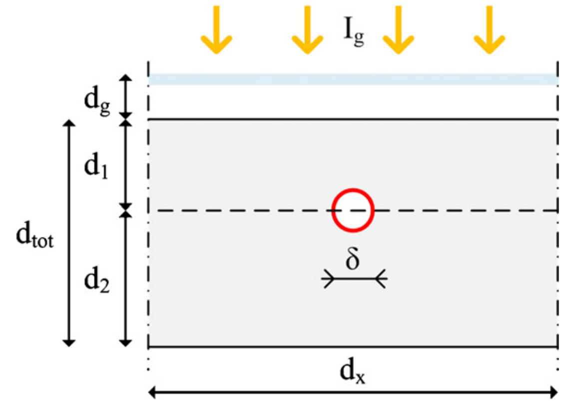

Fig. 3. MSTC elementary unit cell.

The heat transfer in MSTC solid matrix and working fluid is a three- and one-dimensional time-dependent problem, respectively. In order to simplify the analysis, two assumptions can be done. A first affirms that the same temperature distribution exist between any tubes: it implies that the thermal response of the original MSTC geometry corresponds to that of a simplified parallelepiped embedding a single tube and characterized by a width equals to the pipe spacing. A second says that the temperature gradient in any plane perpendicular to fluid direction is larger than the longitudinal one. This simplification leads to divide the MSTC structure in n-segments along fluid direction, in which the fluid temperature can be assumed approximately constant: the greater the number of segments, the better the accuracy in calculating the fluid temperature profile. Each segment is subjected to the same boundary conditions above described and the segments are then coupled together, in a way that the outlet fluid of a unit cell becomes the inlet fluid of the successive one [35–39]. The heat conduction in the solid becomes a 2-dimensional heat transient problem, allowing to study a simplified elementary unit cell (Fig. 3). Edge losses on the MSTC perimeter and the heat transfer occurring in tube headers are usually neglected.

Several numerical methods can be adopted for calculating the solution of the heat conduction problem in a MSTC. In the case of simple collector's geometry, the solution of the three-dimensional problem can be simplified to a one-dimensional one, as described above. In other cases, when MSTCs are conceived with particular geometries, these simplifications are no longer applicable and more detailed methods are required (for instance, Finite Element Method (FEM) or Finite Volume Method (FVM)).

In some of works here reviewed [35–38], the heat conduction has been solved through an explicit Finite Difference Method (FDM). The accuracy in calculating the distribution of temperature in solid is a function of the selected simulation time step and geometry grid spacing. These parameters have to be defined, firstly accordingly to the fulfilment of stability criterion (Fourier number) and secondly, in a way that calculation efforts are within feasible and reasonable limits. For instance, Bosphetty [37] and Nayak [38] carried out a 2-dimensional FDM calculation selecting a grid with a spacing of 5 mm and a time step of 10 s. The stability criterion to fulfil referred to an internal cell is:

$$\mathrm{Fo} = \frac{a\Delta x}{\Delta t^2} = 0.193 \leq \frac{1}{4} \quad (2)$$

Other authors treated the dynamic thermal response in solid matrix using Fourier Series. From a mathematical point of view this is a very elegant approach and this method have been adopted in either single- [59–62] or multi-layered [27,28] structures under different boundary conditions. Because of the problem nature, these should be linear or at least easy to linearize (e.g. solar radiation can

be linearized using the notion of sol–air temperature). The solution of the generic periodic temperature is a function of time, space and number of harmonics chosen. In particular this last parameter is crucial in a way that the greater the number of harmonics, the higher the numerical accuracy, but the more time-consuming calculation is required.

Traditional theory on solar thermal collectors (here denoted with HWB theory [40–44]) is derived from the fin-efficiency method. This method does not take into account capacitance effects of fin-material, because in general heat conduction is prevalent on storing effects. As affirmed in [45], the influence of this issue on traditional metallic FPCs is however negligible and generally the influence of heat storing determines a decrease of the useful energy from 1% to 5% on a daily basis.

Fin-efficiency method adopts the Lumped Capacitance Method (LCM) [46], a method largely used for solving transient heat transfer problems. It based on the assumption that the temperature of the body is spatially uniform and thus the temperature is a function of time only $T(t)$. The validity of this method depends on the resulting Biot number.

$$\mathrm{Bi} = \frac{h_{\mathrm{conv}} d_{\mathrm{tot}}}{\lambda} \tag{3}$$

The criterion to fulfil is Bi < 0.1, which means that heat convection is one order of magnitude greater than heat conduction. Under these conditions the error associated with LCM approach is small. For instance, assuming as convective heat coefficient h_{conv} the value of 15 W/(m^2 K), the Biot number for the case of a copper-absorber in a FPC collector with a plate thickness of 0.5 mm, amounts to $1.9 \times 10^{-5} < 0.1$. In the case of a MSTC this approximation is no longer valid, because under the same boundary conditions, a concrete-made MSTC with thermal conductivity of 1.8 W/(m K) and a total thickness of 100 mm, embedding the pipe coil in the middle section, reaches a Biot number of 0.4 > 0.1.

The large heat capacitance of MSTC determines transient states and so a lag of time is required before steady state conditions are reached. Transient conditions are mostly caused by time-variant boundary conditions (ambient temperature and solar radiation). However, if boundary conditions do not vary significantly, steady-state conditions are met and so collector's parameter derived from HWB theory can be calculated and adopted too. This approach is in general useful because it permits to compare on the same basis performance parameters of different solar thermal collectors, but on the contrary it neglects the effect of heat storing on collector performance, a central aspect for MSTCs. This approach has been adopted by Sokolov [39], which conducted several numerical simulations in order to study the influence of independent (pipe spacing or slab thickness) and dependent (heat transfer coefficient or heat loss coefficient) design parameters, as well as boundary working conditions (incident solar radiation, inlet fluid temperature) on collector energy efficiency. Collector's parameters, such as efficiency factor F', heat removal factor F_R and instantaneous energy efficiency η have been calculated when these conditions are verified only and the relative time required to meet this state is denoted with t_∞: this value amounts to approximately 5 times the time constant of the elementary section.

$$F_{\mathrm{R}} = \frac{I_{\mathrm{g}} c_{\mathrm{p,f}}}{U_{\mathrm{L}}} \left[1 - \exp\left(-\frac{U_{\mathrm{L}} F'}{I_{\mathrm{g}} c_{\mathrm{p,f}}} \right) \right] \tag{4}$$

$$F' = \frac{U_0}{U_{\mathrm{L}}} \tag{5}$$

$$\eta = a_0 - a_1 \frac{T_{\mathrm{f,av}} - T_{\mathrm{air}}}{I_{\mathrm{g}}} - a_2 I_{\mathrm{g}} \left(\frac{T_{\mathrm{f,av}} - T_{\mathrm{air}}}{I_{\mathrm{g}}} \right)^2 \tag{6}$$

or alternatively:

$$\eta(t) = \frac{q_{\mathrm{u}}(t)}{\alpha I_{\mathrm{g}}(t)} = \frac{\dot{m}_{\mathrm{f}} c_{\mathrm{p,f}} (T_{\mathrm{f,out}} - T_{\mathrm{f,in}})}{\alpha I_{\mathrm{g}}(t)} \tag{7}$$

MSTCs are equivalent to radiant systems exposed outdoors, but unlikely from these, pipes are means for collecting heat from the environment. With regards to numerical analysis, radiant systems are based on fin-efficiency method as well as FPCs and so in general these methods [47–50] (for sake of brevity only few are mentioned) are applicable also for MSTCs. A notable effort in solving the problem of heat transfer from/to radiant systems is the work of Koschenz and Lehmann [50], which derived and validated a numerical model for simulating the response of thermally activate structures, based on [51,52] references. As in electric circuit's theory, a Delta-Star transformation can be performed between three nodes, which in this case correspond to the fluid and surface temperatures. Doing this a fictive additional node is inserted, representing the core temperature of the massive element. The heat transfer between fluid and core temperature is pure conductive, in which an equivalent thermal resistance has been calculated as a function of pipe network configuration, pipe diameter, fluid mass flow rate and temperature. The heat transfer to/from the environmental boundary condition from/to the fictive core temperature is then distributed accordingly to the thermal characteristics of the layers. This method has been implemented in Trnsys [53] and applied for the calculation of massive structures in [54–56]. The heat conduction problem is here solved with the Transfer Function Method [57,58], a method developed from Response Factor Method (RFM) and based on Laplace transforms. The major advantage in doing this is that the two-dimensional heat transfer can be further simplified to a one-dimensional problem. Nevertheless, the calculation of high-capacitance structures should take care of convergence problems: in order to fulfil this requirement, the time period (known as time-base) on which RFM is based has to be a finite number of times the simulation time step.

Furthermore, accordingly to the detail of physical analysis, three different approaches can be considered in modelling a thermal system [63]. A black-box numerical model solves a thermal problem without any reference to underlying physics. In this, usually empirical rules are used, which relate the output of the model to a set of inputs. In a grey-box approach, some or all of the mechanisms describing the behaviour of a system are known, but are not fully represented in the model and approximated rules are used. Bulk or lumped parameters and approximated rules are here typically used. Finally, the white-box approach describes accurately the behaviour of a real system by rigorous physical equations in which no approximations are made using bulk parameters. In the literature here reviewed, the most used approaches are grey-box, in which mostly analytical methods are applied for solving the conduction problem in solid matrix. White-box method is only adopted in [35–38], where FDM is used to solve conduction heat transfer.

4. Applications of MSTC

An advantage in using concrete as absorber surface is the great variety of structures in which a pipe coil can be embedded. Thanks to this, MSTCs can be implemented in horizontal, sloped or vertical installations. Authors such as Spencer [64], Bainbridge [65], Sedwhich [66], Olive [67] and Turner [68,69] were the pioneers of studying the feasibility of MSTCs as solar systems. Several applications (swimming pool heating, DHW heating or preheating, combined SH and DHW) and system layouts (gas boiler, parallel or series heat pump) have been developed. In these, MSTCs are applied in low temperature range and they are meant as possible substitutes for FPCs.

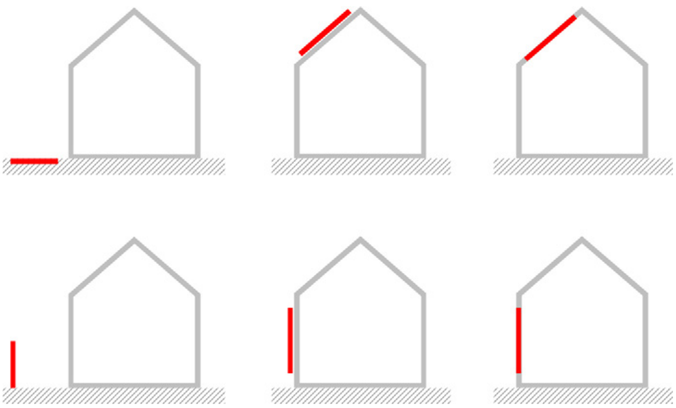

Fig. 4. Classification of MSTC application accordingly to degree of building integration.

MSTCs can be classified accordingly to different criteria. A first classification distinguishes among heating, cooling or DHW applications, putting in evidence the purpose to which MSTC are adopted. Then looking at the fulfilment of building loads, the collected heat can be used directly or indirectly. A direct exploitation occurs when solar energy covers partially or entirely DHW and/or SH load or when the collected heat from MSTC leads to a reduction of indoor temperature, partly covering the cooling demand. On the other hand, indirect applications are those where the collected heat from MSTC is used as source for an heat generator system. Typically, heat pumps are used for these purposes: the heat stored in MSTC is used as low grade heat source until heat pump working conditions are satisfied. When the heat pump is down, MSTC recharges from the environmental energy for further utilizations. Moreover, accordingly to the degree of integration in building envelope, MSTCs can be classified in detached, partially integrated or integrated systems (Fig. 4). In order to sort the reviewed applications, this classification is adopted in the next section. It permits effectively to highlight advantages and drawbacks, independently from the system layout in which MSTC are implemented. In order to better compare technological and thermal features, two synoptic tables (Tables 1 and 2) have been developed, listing a series of relevant parameters of MSTCs, such as the thermal properties of the massive material, the pipe tube, the working fluid, the application and the installation mode.

4.1. Detached MSTC

The minimum degree of integration of solar systems occurs when MSTCs are physically separated from the building envelope. To this category belong structures such as horizontal pavements, vertical external walls or prefabricated structures, which are not in direct contact with the building. In terms of orientation and tilt angle, these surfaces are usually not optimized for solar energy collection, because they are conceived for meeting others functions than solar thermal purposes. Anyhow, these structures represent alternatives and solar-potential free surfaces, in most of the cases.

The feasibility of using horizontal concrete structures has been firstly studied by Turner [68,69] and Srivastava [60]. Turner investigated the solar-potential of ground-integrated MSTCs during the summer and winter season in North America. He introduced the concepts of heat removal temperature T_s and initial energy investment (IEI). The first is defined as the fixed set-point temperature for starting to remove heat from the slab, while the second is the amount of energy needed for increasing the temperature of the leaving fluid up to T_s and it represents a non-recoverable term. When the temperature T_s increases, the daily useful heat collection decreases, because a greater value of IEI is necessary. By moving the pipe position in depth the initial energy investment increases, because the distance between the length penetration of heat wave and the fluid becomes greater. The author affirmed that the notion of instantaneous efficiency η is meaningless for MSTC, because the heat extraction can occur also when the intensity of solar radiation is close to zero (e.g. cloudy conditions) are present. Thus, a daily efficiency η_d figure:

$$\eta_d = \frac{\int q_u(t)dt}{\alpha \int I_g(t)dt} \tag{8}$$

has been adopted in order to overcome such limits. Srivastava [60] compared the performance of inexpensive ground-integrated solar collectors. The response of ground, sand and concrete have been numerically calculated: thanks to a greater thermal diffusivity, concrete resulted the best material.

Gao [70] and Wu [71] applied the concept proposed by Turner to a road hydraulic circuit, which is used as solar collector during the summer and as ice-snow melting system during the winter. The authors demonstrated that the daily efficiency of the solar system increased with an increment of the flow rate (from 70 l/h to 100 l/h), while a lower fluid inlet temperature would promote a better heat collection. The potential of such surface was quantified in 150–250 W/m^2 with a solar radiation of 300–1000 W/m^2. As further benefit, the system could contribute in reducing the local heat island effect in built up areas, by removing the absorbed radiation. The contribution could be important in particular in urban context where structures like urban roads or parking areas could be free exploitable surfaces.

Probably, the most significant contribution in studying MSTC is the activity that Fraunhofer-Institute for Building Physics conducted in the 1980s [17,18,24,72–74]. They published numerical and field test results of several massive collector prototypes. The energy response of MSTC has been described through the specific effective heat flux extracted from the collector $q_{u,eff}$ [W/(m^2 K)], which corresponds to the ratio between the collected heat per unit area and the difference between the ambient and fluid average temperature. Indeed, in MSTCs the influence of ambient air temperature is central as well as solar radiation, because if the fluid is colder enough, MSTC can extract heat from the relatively warmer ambient air, also during the night. If specific heat q_u [W/m^2] gives a measure of the intensity of collected heat, the effective specific heat $q_{u,eff}$ permits to understand the quality of the delivered energy.

$$q_{u,eff} = \frac{q_u}{T_{air} - T_{f,av}} \tag{9}$$

In particular a concrete vertical wall is discussed in [72–74]. Several constructive parameters have been varied in order to investigate the sensitivity of the system with regards to pipe coil position, concrete thermo-physical properties, finishing and colouring of external surfaces. Field tests confirmed that MSTC performance is positively affected by (1) a decrease of the pipe spacing (ranging from $q_{u,eff}$ of 19.3 W/(m^2 K) with a pipe spacing of 125 mm to 25 W/(m^2 K) with a pipe spacing of 65 mm), (2) a greater MSTC thickness, reaching a value of 24.8 W/(m^2 K) and (3) a ribbed external finishing, which had a double exposed surface than the base case configuration, in terms of specific effective heat (+9%) and of reduction of frost formation. Finally, the influence of orientation and surface colour has been investigated. As expected, dark coloured finishing are highly recommended and southern surface was the most attractive orientation.

More recent works [54,55] investigated the feasibility of coupling a precast concrete garage as a heat source for a brine to water heat pump. The garage had a gross volume of 46.5 m^3 and an exposed surface of 73.5 m^2. Heat pump capacity covers the heating (30 kWh/m^2) and DHW (50 l/person/day at 40 °C) demand

of a single family house located in a typical European climate (Stuttgart, Germany). Numerical simulations have been carried out, in which the feasibility of the mentioned system is compared with air-source heat pump systems. In general, they concluded that garage-absorber has a good potential in particular during mid-seasons, where the combined effect of low-heating demand and solar gains becomes profitable in terms of heat pump driving temperatures. Dark colored surfaces should be preferred to lighter finishing, because of the greater absorbed radiation.

4.2. Partially integrated MSTC

From the literature review conducted, it emerged that the most common application of MSTCs are roof-installed systems, as variants to traditional FPCs. Massive collectors can be provided by a glass pane [11,37,38,75–78], but also they are meant as unglazed massive collector [79].

A comprehensive investigation on alternative materials that can be adopted for solar thermal purposes has been described by Kutscher [11]. Here, two prototypes of MSTCs have been conceived, a first that had an open channel design with a glazing glass directly bounded to absorber structure, and a second where the passageways were obtained during the casting phase and no plastic or metallic pipes were used. Both configurations had an exposed area of 2 m^2 and were made of glass-reinforced concrete (GRC). This material is cheap and it combines good thermal properties to strengthen resistance, because of the addition of glass fibres to concrete mixture. The second configuration showed some problems, mainly due to the imperfect sealing of the cavities in it. The problem was solved by using liquid sealants within the fluid passageways.

Bosphetty [37] and Nayak [38] studied experimentally the performance of a solar concrete collector for providing DHW in New Delhi (India). They conducted tests on thermal, pressure lost and static issues. In particular on the thermal side, they noted that by decreasing the pipe spacing from 15 cm to 6 cm, the collector efficiency increased appreciably, because of a more effective heat removal from concrete absorber. A further positive effect is also testified by doubling the fluid flow rate from 0.01 kg/s to 0.02 kg/s. This variation decreases absorber's temperature, reducing heat losses and leading to an increase of the daily efficiency. Finally, they compared between a serpentine and a parallel configuration of the pipe network and it emerged that for the first model the final pressure amounted to 8.4 mm of water, which corresponded to nearly 10 times the value of the second arrangement.

Al-Saad [75] developed three glass-covered MSTC configurations, testing their behaviour in Jordanian climate. Collectors differed merely on the tube material employed (galvanized steel, thermo pipe, PVC). In general, collector performance has been calculated in terms of daily efficiency and the value amounted to about 50%. The behaviour of MSTC was positively affected by an increase of fluid mass flow rate (from 0.011 kg/s/m^2 to 0.033 kg/s/m^2), leading to an increase of the maximum efficiency. Compared to traditional FPCs, MSTCs operated at a wider range of inlet temperature (a lower slope of efficiency curve), although the maximum efficiency was generally smaller (a lower curve intercept). The time constant of the three concrete absorbers has been calculated. The values were greater than traditional metallic collectors with values range from 20 min (galvanized steel tubes) to 33.6 min (thermo pipe tubes). Because of the better thermal conductivity of the material, galvanized steel tubes revealed a better behaviour than plastic pipes. In MSTC this parameter is central, because it improves the heat transfer to the fluid accordingly to the boundary conditions.

The MSTC configurations developed in [75] has been afterwards evaluated by Jubran [76] within three different plant layouts taken from [34]. A space heating and domestic hot water system (SHDHW), a domestic hot water system (DHW) and a solar swimming pool heating system (SPHS) have been studied for Amman (Jordan) weather conditions through the *f*-chart method [34]. The space heating design load and setpoint temperature were fixed at 20 kW and 22 °C, respectively. The DHW draw-off was assumed to 300 l at 60 °C, while the water setpoint temperature for the SPHS system was fixed to 28 °C. A parametrical analysis has been carried out by varying collector's field area. In the case of SHDHW layout, the optimum MSTC surface was of 55 m^2 with a minimum solar fraction (SF) of 27%. In the DHW system, 5 m^2 of MSTCs permitted to cover 52% of the mentioned load, while a conventional FPC typically covers the 45%. Increasing the collector's field to 15 m^2, the solar fractions reached for concrete and traditional collectors were 87% and 75%, respectively. In the SPHS system, the solar fraction was linearly dependant to the collecting area and in particular it ranged from 10% with 100 m^2 up to 40% with 400 m^2 of concrete collectors. The outcomes of this work affirmed that in general MSTCs reached higher annual and monthly solar fractions than traditional metallic solar collector.

In [77,78] the performance of an integrated solar storage collector concept is reported. The collector has been exposed outdoor and monitored for three months in Tunisian weather conditions. The monitoring results showed that during a typical sunny day in winter the solar collector outlet water increased up to 50 °C at noon remaining almost constant for 3 h: in this case the maximum useful gain was of 2.9 kW. During partially shaded winter days, outlet fluid temperature is not deeply affected by a fluctuation of solar radiation because of the thermal inertia of concrete structure. On the other hand, the high thermal loss coefficient U_L determined higher heat losses during the night compared to traditional solar systems. The heat loss coefficient amounted to 14 W/(m^2 K), which corresponded to twice the value of unglazed solar collectors (8 W/(m^2 K)) [34,80]. Furthermore, the author carried out an energy and exergy analysis. Energy and exergy daily efficiencies amounted to 15% and 32%, respectively, where the corresponding values for traditional FPCs are 52% and 4% [81].

A different MSTC concept has been developed by Chaurasia [79]: the collector had no glass panes on the collector top and no insulation at its back has been used. The aim of this collector was to fulfil DHW load for Jodhpur (India) location. The network of pipe is arranged in a parallel configuration and embedded in collector structure in a way that 70% of their external area laid inside of the concrete matrix and the remaining 30% is directly exposed outdoors. Three different inclinations (horizontal plane, 41° toward south and vertical) has been tested, but the best results came from the tilted configuration. The system is suited for producing water at moderate temperature (36–58 °C) and permitted the production of 25–40 l/m^2 of hot water. The author affirmed that such system could be employed for water pre-heating to any heating system and in particular during the summer season for supplying hot water a relatively higher temperature.

4.3. Building integrated MSTC

As previously said, a decisive strategy to reduce the investment cost of traditional solar collectors is to enhance the integration degree of solar system in building façade.

Sarachitti [25] and Kumar [62] studied the performance of a roof-integrated MSTC in Thailand and India, respectively. Both systems consisted of a concrete matrix, in which a network of tubes is embedded. Experimental outcomes showed the effect of heat removal on surface and indoor air temperatures, which resulted in a decrease compared to a traditional configuration. Experimental results [25] showed that MSTC can produce up to 40 l of hot water per day at temperatures ranging from 40° to 50 °C. They emphasized the potential of designing the building's roof as solar collector/storage systems, not only for DHW preparation but more

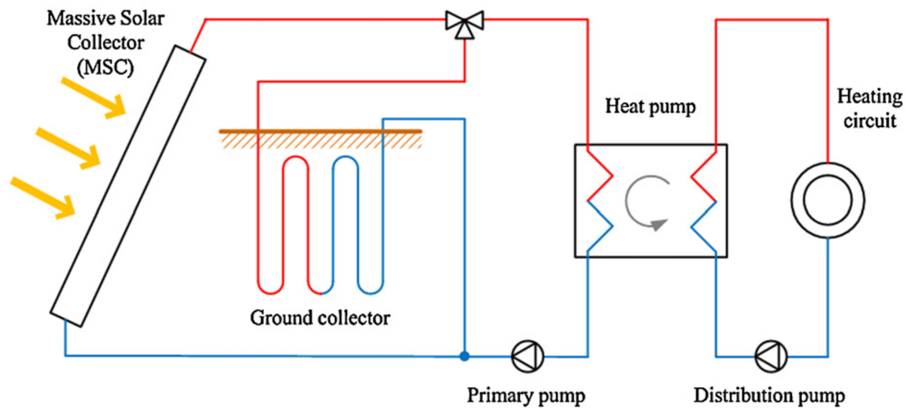

Fig. 5. Parallel heat pump system between roof integrated MSTC and ground collector [82–86].

as active strategy to reduce cooling loads. Increasing the water flow rate from 2.5 l/h/m^2 to 20 l/h/m^2, a significant improvement in collector's performance due to the reduction of solar gains through roof structure has been noted, with a contemporary reduction of the outlet fluid temperature [62]. Moreover, a sensitivity analysis of pipe plane position has been carried out: the collected heat is notably reduced and the relative peak shifted in time up to 12 h with respect to solar radiation maximum value.

The indirect exploitation of MSTC collected energy has been firstly investigated in [17,18]. A roof-integrated MSTC fed a dual-source heat pump, in which a ground heat exchanger acted as secondary heat source. DHW and SH loads of a single family house are met by the plant scheme depicted in Fig. 5. In [82–86] the monitoring results of an installation in a 150 m^2 SFH in Stuttgart (Germany) are reported. The heat pump capacity was 18 kW and the system is designed in a way that 1/3 of the final energy is fulfilled by the ground collectors and the remaining 2/3 by the MSTC. The seasonal efficiency of heat pump (SCOP) amounted to 2.8, ranging from 2.5 to 3.2 during the year. In residential contexts, in which noise level are limited or local drilling due to space limitations are not permitted, this system could become an alternative to air-source or ground coupling heat pumps [85].

Abbott [35,36] developed a concept of a concrete roof assembly coupled with a solar assisted heat pump (SAHP). Numerical simulation have been carried out for Chicago and Atlanta climates. The collector is conceived as a precast panel that would be easily implemented within the building structure. Outer layer is covered by a glass pane and the air gap permitted an increase solar heat gains and a reduction the thermal losses to the environment. The plant layout integrated a liquid–air heat pump and a cold storage tank (Fig. 6). The solar energy is stored in the storage tank, which served as source for the heat pump's evaporator. The system is designed to fulfil the heating loads of a typical residential single family house in the US of 4 persons, with a DHW daily drawn-off of 62 l/day. The outlet fluid temperature of MSTC was a function of solar radiation magnitude, heat pump operation and building loads. In both locations, it ranged from 0 °C to 30 °C in a typical winter design day. The thermal efficiency of MSTC reached a value of about 40%. The MSTC coupled to a heat pump is then compared to a reference air-to-air heat pump system. The results showed a reduction of the electric energy for MSTC system, because of the greater inlet temperature in evaporator heat pump than the ambient air and in general, the larger the heating season, the larger the savings.

Within FP7 project "Cost-Effective" [87], a facade-integrated solar heat pump system for fulfilling heating load has been developing. The concept aimed to overcome the space limitations of installing solar thermal panels typical for high-rise buildings. The driving idea was that the building facade represents a free area which can be provided by means of collecting solar radiation. Numerical simulations of the system above described has been carried out [88] for Freiburg climate (Germany): the system is coupled to a test reference room of 38 kWh/m^2 of seasonal heating demand with a setpoint temperature of 20 °C. The external opaque surface had a light colour and the collector surface was 2.5 m^2. The results showed that heat pump performance is positively affected by the presence of the facade collector also during the cold season. Nevertheless, the Seasonal Performance Factor (SPF) of the system was not so satisfactory, achieving an ultimate maximum value of 3.1. The heat pump prototype performance diverged from expected efficiencies (COP = 3.7) at B0/W35 test condition, to the measurements (COP = 2.9). This variation was due to the small-scale of the heat pump, in which heat losses from compressors and pipes became more evident. The concept proposed seems to be realistically improvable in crucial aspects, such as the heat pump design and the lack of the optimization of the external radiant system. As a conclusion, the authors recognized the need to limit the heat collection until when condensation and frost formation conditions on the outer surface of the opaque element occur (Fig. 7).

The authors of [89–91] conducted similar research activities, investigating the feasibility of using a roof-integrated MSTC system. Further from the benefits above mentioned, the authors affirmed that such system can be adopted in hedged-in urban context, typical of Italian cities, in which local regulations limit the installation of roof solar system. The MSTC is directly connected to heat pump and high temperature water storage is used in order to decouple building loads and solar availability. Nevertheless, this configuration is characterized by higher heat losses from the storage mantle than the system layout adopted in [88]. A quasi-steady state

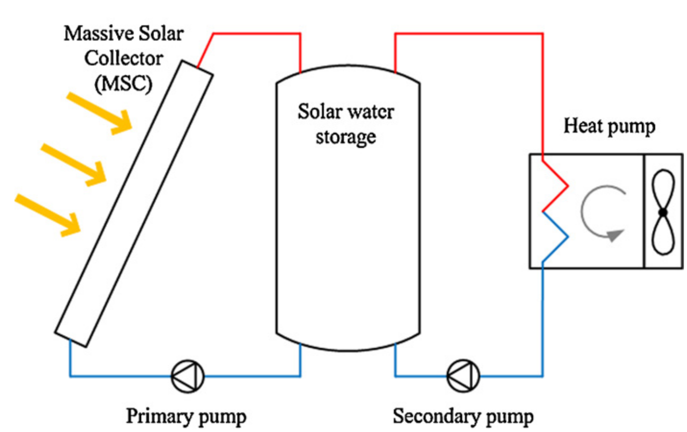

Fig. 6. MSTC acts as evaporator's source for a liquid–air heat pump [35,36].

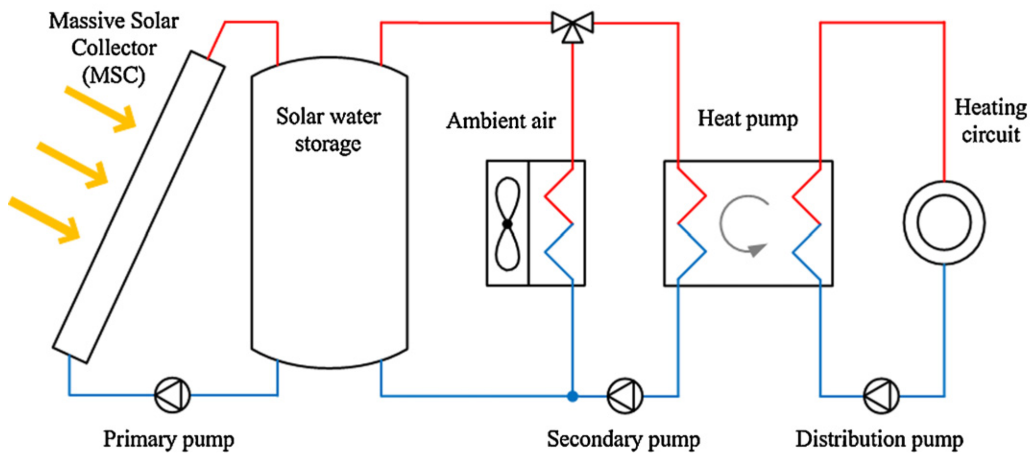

Fig. 7. MSTC implemented in a dual source heat pump [88].

calculation has been carried out; the specific collected solar energy was calculated as follows:

$$q_u = (T_{sa} - T_{f,av}) \cdot U_e + (T_{air} - T_{f,av}) \cdot U_i \quad (10)$$

The energy collected is the sum of two energy contributions, which come from outdoor and indoor. Both terms are directly dependent on the external and internal U-values (U_e, U_i): the greater the value, the grater the contribution. As external boundary temperature, sol–air temperature T_{sa} is used. The simulation results showed that the SCOP was a function of the ratio between MSTC area and the conditioned living area; for the considered Italian locations, a ratio above 0.6 led to a SCOP of 3.5. Compared to a reference plant (gas boiler), the energy savings in terms of primary energy are quantified in about 30% in these conditions (Fig. 8).

4.4. Final remarks

What clearly emerged from the literature review is the lack of a homogenous thermal and energy analysis and that the information regarding collector configurations, performance figures and designing methods are fragmented (see Tables 1 and 2). Concerning the performance figures of MSTC, some authors adopted the notion of instantaneous energy efficiency conceived for massless solar collectors, while others preferred to use the effective specific heat, which takes into account the collected heat per area scaled by the temperature difference between fluid and environment. These discrepancies make difficult a comparison among similar configurations.

Even if many design parameters are missing, several analogies can be found. The energy performance of a MSTC is a multi-variable problem, in which parameters such as pipe diameter and spacing, thermo-physical properties of massive matrix and the presence of a glass coating have a key role. MSTC energy efficiency is positively influenced by a low pipe spacing, a great pipe diameter, a reduction of the top loss coefficient, a great thermal diffusivity of concrete, a low inlet fluid temperature and an high solar absorptivity. Concrete is mainly used in MSTCs, because it combines good thermo-physical properties with a high workability and stability to thermal stresses. Plastic pipes better combine withstanding against thermal stresses and cost savings, even if they have a lower thermal conductance compared to metallic ones.

MSTCs have been mostly suggested for covering DHW in hot climates (Thailand and Middle East) and both DHW and SH loads in moderate climates (central and southern Europe and U.S.A.). The solar incident radiation band in which MSTC operates more effectively is included within 150 and 800 W/m^2 [39,70,71]: above this level the solar collection is inhibited because of larger radiant thermal losses. A direct fulfilment of building loads is achieved when solar availability is sufficiently high and for example a glazed MSTC with an aperture area of 2 m^2 can cover up to 80% of DHW demand [77,78]. On the other hand, in less insulated regions, indirect applications are adopted using the MSTC as low-grade heat source for a compression heat pump. In this last case, monovalent or

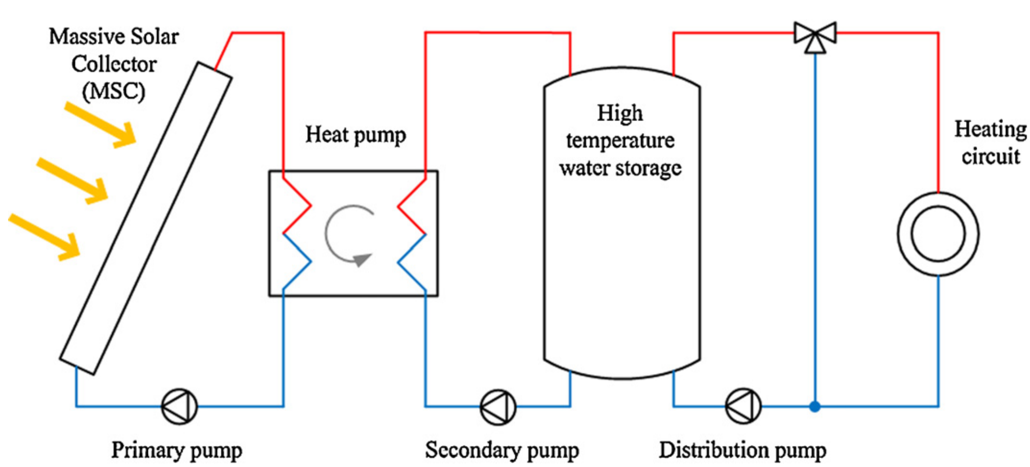

Fig. 8. MSTC is directly fed the evaporator of liquid–liquid heat pump [89–91].

bivalent systems can be even present, as well as single- or dual-source heat pumps. Heat pump systems can cover DHW and SH loads and the SCOP ranges between 2.8 and 3.5 [82–85,89–91] accordingly to the peculiarities of the cases. The presence of a thermal storage is generally needed, in order to decouple solar collection phase and building energy demand phases, preferring cold- to hot-storages. As reported in [85], the SCOP of combined MSTC and heat pump is usually 10% less than ground-source heat pumps (SCOP = 3.4, [92]).

5. Conclusions

Concrete is a very interesting material for solar thermal collector construction, because it combines good thermo-physical properties with a high workability and stability to thermal stresses. Thank to this, concrete structures can be potentially adopted as solar thermal collectors (here defined as Massive Solar-Thermal Collectors – MSTC) and a great variety of installations and typologies can be derived. Nevertheless, up to the present very few MSTC commercial products have been released on the market and mostly prototypes or ad hoc systems have been developed and tested.

Compared to traditional FPCs, MSTCs behave similarly to these in low temperature range (delivered fluid temperature < 50 °C) and the share of solar energy is dependant to several aspects, such as building loads, solar availability and plant scheme solutions. The thermal behaviour of a MSTC is a multi-variable problem, in which constructive parameters and operational conditions play an important role.

Accordingly to the degree of integration with respect to the building envelope, a classification among detached, partially or fully building integrated MSTC systems has been derived. Any of these variants are characterized by a more or less intense heat removal, which should be accurately studied and considered in the design phase. When a better integration of solar thermal technologies within building envelope is aimed, the boundaries between mere passive and active solar systems are overcome. By definition, the building envelope is a passive solar system, because it can store energy thanks to the high thermal capacity without no additional pumping work. If it is used as solar absorber, it acquires peculiarities of an active system and thus, the distinction between active and passive systems becomes more difficult or even meaningless.

The integration of collected energy from MSTC to building loads can be direct, (e.g. DHW heating or preheating), or indirect, mainly by operating the MSTC as low-grade heat source for liquid-source heat pumps. This application has been studied in recent works mostly and applied in those cases where DHW and SH demands are present. In order to overcome the time-lag between solar availability and building demand, thermal energy storages are typically necessary. If favourable conditions are met, a monovalent operation of heat pump can occur: in other cases, dual-source heat pumps (air- or ground-coupled systems) or auxiliary heaters (electrical back-up or gas boiler) should be considered. The application of MSTC for covering the cooling demand is here achieved simply by removing the solar gains on opaque structures: the effectiveness of this strategy is a function of solar intensity during and related building loads.

Several aspects are still necessary to be addressed. For instance, it should be clarified which is the most effective trade-off between heat storing and extraction from MSTC, which is the fraction of the useful heat collected from ambient air and solar radiation, which is the dependency on the useful energy of MSTC design parameters (pipe spacing, diameter, etc.) and boundary conditions (climate and loads). Further, monitoring and experimental activities should be performed in order to clarify medium- and long-term MSTC working conditions and reliability, specific system components (e.g. small capacity heat pumps) should be designed and manufactured and more energy concepts and system layouts need to be studied in order to get a clear picture of this topic.

References

[1] Kalagirou SA. Solar thermal collectors and applications. Prog Energy Combust Sci 2004;30:231–95.
[2] Jaisankar S, Ananth J, Thulasi S, Jayasuthakar ST, Sheeba KN. A comprehensive review on solar water heaters. Renew Sustain Energy Rev 2011;15:3045–50.
[3] Hossain MS, Saidur R, Fayaz H, Rahim NA, Islam MR, Ahamed JU, et al. Review on solar heater collector and thermal energy performance of circulating pipe. Renew Sustain Energy Rev 2011;15:3801–12.
[4] Wyman C, Castle J, Kreith F. A review of collector and energy storage technology for intermediate temperature applications. Sol Energy 1980;25:517–40.
[5] Kreith F, Löf GOG, Rabl A, Winston R. Solar collectors for low and intermediate temperature applications. Prog Energy Combust Sci 1980;6(1):1–34.
[6] Lenel UR, Mudd PR. A review of materials for solar heating systems for domestic hot water. Sol Energy 1984;32(1):109–20.
[7] O'Brien-Bernini F, McGowan JG. Performance modelling of non-metallic flat plate solar collectors. Sol Energy 1981;33(3/4):305–19.
[8] International Energy Agency (IEA) – Solar Heating & Cooling (SHC). Task 39 – polymeric materials for solar thermal applications. http://www.iea-shc.org/task39/.
[9] Brechlin U, Pilgaard O, Piria R. Sun in Action II – a solar thermal strategy for Europe. Brussels, Belgium: European Solar Thermal Industry Federation (ESTIF); 2003.
[10] Hasset R. Solar water heating development at DOE. U.S. Department of Energy, Energy Efficiency and Renewable Energy; 2008.
[11] Kutscher C, Davenport R, Farrington R, Jorgensen G, Lewandowski A, Vineyard C. Low-cost collectors. System development progress report Golden, CO, USA: Solar Energy Research Institute; 1984.
[12] International Energy Agency (IEA) – Energy Conservation in Building & Communities Systems (ECBCS). Annex 44 – Integrating Environmentally Responsive Elements in Buildings. http://www.ecbcs.org/annexes/annex44.htm.
[13] Munari-Probst MA, Roecker C. Towards an improved architectural quality of building integrated solar thermal systems (BIST). Sol Energy 2007;81:1104–16.
[14] Munari-Probst MA. Architectural integration and design of solar thermal systems. PhD Thesis submitted at École Polythechnique Fédérale de Lausanne EPFL, Switzerland; 2009.
[15] Hestnes AG. Building integration of solar energy systems. Sol Energy 1999;67(4–6):181–7.
[16] Bergmann I. Facade integration of solar thermal collectors a new opportunity for planners and architects. Renew Energy World 2002;5(3):89–97.
[17] Schwarz B. Wärme aus Beton. Systeme zur Nutzung der Sonnenenergie. Düsseldorf, Germany: Beton-Verlag GmbH; 1987.
[18] Primus I-F. Massivabsorber. Die Wärmequelle für die Wärmepumpe. Düsseldorf, Germany: Beton-Verlag GmbH; 1995.
[19] Zhang Y, Zhou G, Lin K, Zhang Q, Di H. Application of latent heat thermal energy storage in buildings: state-of-the-art and outlook. Build Environ 2007;42:2197–209.
[20] Lee T, Hawes DW, Banu D, Feldman D. Control aspects of latent heat storage and recovery in concrete. Sol Energy Mater Sol Cells 2000;62:217–37.
[21] Zhang D, Li Z, Zhou J, Wu K. Development of thermal energy storage in concrete. Cem Concr Res 2004;34:927–34.
[22] Hawes DW, Banu D, Feldman D. Latent heat storage in concrete. Sol Energy Mater 1989;19:335–48.
[23] Hawes DW, Banu D, Feldman D. Latent heat storage in concrete II. Sol Energy Mater 1990;21:61–80.
[24] Schwarz B, Künzel H, Mechel FP. Feuchtigkeitsverhältnisse in Beton-Absorberelementen. Stuttgart, Germany: Fraunhofer-Institut für Bauphysik IBP; 1982.
[25] Sarachitti R, Chotetanorm C, Lertsatitthanakorn C, Rungsiyopas M. Thermal performance analysis and economic evaluation of roof-integrated solar concrete collector. Energy Buildings 2011;43:1403–8.
[26] Bilgen E, Richard MA. Horizontal concrete slabs as passive solar collectors. Sol Energy 2002;72(5):405–13.
[27] Cossali GE. The heat storage capacity of a periodically heated slab under general boundary conditions. Int J Therm Sci 2007;46:869–77.
[28] Cossali GE. The dynamic storage capacity of a periodically heated slab. Int J Therm Sci 2007;46:342–8.
[29] EN 12975-2:2006. Thermal solar systems and components – solar collectors. Part 2: test methods. CEN; 2006.
[30] Marmoret L, Flouannec P, Douzane O, t'Kint de Rooodenbeke A, Quebeudec M. Use of a cellular clayey concrete for a wall specially fitted with water pipes. Energy Buildings 2000;31:89–95.
[31] EN 206-1:2006. Concrete. Part 1: specification, performance, production and conformity. CEN; 2006.
[32] Mehta P, Monteiro PJM. Concrete: microstructure, properties and materials. McGraw-Hill: New York; 2006.
[33] Pigeon M, Marchand J, Pleau R. Frost resistant concrete. Constr Build Mater 1996;10(5):339–48.
[34] Duffie JA, Beckmann WA. Solar engineering of thermal processes. New York: Wiley; 1980.

[35] Abbott AB. Analysis of thermal energy collection from precast concrete roof assemblies. Master Thesis submitted to the faculty of Virginia Polytechnic Institute; 2004.
[36] Abbott AB, Ellis MW. Analysis of thermal energy collection from precast concrete roof assemblies. In: Proc.: ASME Energy Sustainability Conference. 2007.
[37] Bopshetty SV, Nayak JK, Sukhatme SP. Performance analysis of a solar concrete collector. Energy Convers Manage 1992;33(11):1007–16.
[38] Nayak JK, Sukhatme SP, Limaye RG, Bopshetty SV. Performance studies on solar concrete collectors. Sol Energy 1989;42(1):45–56.
[39] Sokolov M, Reshef M. Performance simulation of solar collectors made of concrete with embedded conduit lattice. Sol Energy 1992;48(6):403–11.
[40] Hottel HC, Woertz BB. The performance of flat-plate solar-heat collectors. Trans ASME 1942;64:91–114.
[41] Hottel HC, Whillier A. Evaluation of flat-plate collector performance. Part 1. In: Trans. of the Conf. on the Use of Solar Energy, University of Arizona Press, vol. 2. 1958. p. 74–110.
[42] Bliss RW. The derivations of several plate efficiency factor in the design of flat-plate solar-heat collectors. Sol Energy 1959;3:55–64.
[43] Whillier A, Saluja G. Effects of materials and construction details on the thermal performance of solar water heaters. Sol Energy 1965;9(1):21–6.
[44] Whillier A. Design factors influencing collector performance. Low temperature engineering applications of solar energy. New York: ASHRAE; 1967.
[45] Klein SA, Duffie JA, Beckman WA. Transient consideration of flat-plate solar collectors. Trans ASME – J Eng Power 1974;96A:109–13.
[46] Incropera FP, Dewitt DP, Bergman TL, Lavine AS. Fundamentals of heat and mass transfer. Los Angeles: John Wiley & Sons; 2007.
[47] Kilkis IB, Sager SS, Uludag M. A simplified model for radiant heating and cooling panels. Simulat Pract Theory 1994;2:61–76.
[48] Weber T, Jóhannesson G. An optimized RC-network for thermally activated building components. Build Environ 2005;40:1–14.
[49] Jin X, Zhang X, Luo Y. A calculation method for the floor surface temperature in radiant floor system. Energy Buildings 2010;42:1753–8.
[50] Koschenz M, Lehmann B. Thermoaktive Bauteilsysteme TABS. Dübendorf: EMPA; 2000.
[51] Glück B. Strahlungsheizung–Theorie und Praxis. Berlin: VEB Verlag für Bauwesen; 1981.
[52] Glück B. Wärmeübertragung–Wärmeabgabe von Rohrheizflächen und Rohren. Berlin: VEB Verlag für Bauwesen; 1989.
[53] Klein SA, et al. TRNSYS 16: a transient system simulation program. University of Wisconsin, Madison, USA: SEL; 2006.
[54] Krause M. Potentialuntersuchungen zur Verwendung von Stahlbeton-Fertiggaragen als Wärmequelle: Phase 1. Kassel: Fraunhofer-Institut für Bauphysik IBP; 2009.
[55] Krause M, Schalk K. Potentialuntersuchungen zur Verwendung von Stahlbeton-Fertiggaragen als Wärmequelle: Phase 2. Kassel: Fraunhofer-Institut für Bauphysik IBP; 2009.
[56] D'Antoni M. Solar Collector Concrete Panel (SCCP). Feasibility analysis of concrete structures utilization for solar collection. PhD Thesis submitted at University of Udine; 2011.
[57] Stephenson DG, Mitalas GP. Calculation of heat conduction transfer functions for multi-layer slabs. In: ASHRAE Annual Meeting. 1971.
[58] Mitalas GP, Arsenault JG. Fortran IV program to calculate z-transfer function for the calculation of transient heat transfer through walls and roofs. Ottawa: Division of National Research Council of Canada; 1972.
[59] Sodha MS, Srivastava A, Tiwari GN, Kaushik SC. Performance of a constant flow sand solar collector. Appl Energy 1980;7:201–14.
[60] Srivastava A, Hussain SQ, Sharma BN, Tiwari GN. Thermal performance of ground as an inexpensive solar collector and storage system. Energy Convers Manage 1982;22(3):197–204.
[61] Singh S, Bhardwas SS, Bansal NK. Heat transfer coefficient for constant flow solar collector/storage systems. Appl Energy 1982;10:151–8.
[62] Kumar A, Singh U, Srivastava A, Tiwari GN. Thermal design of a roof as an inexpensive solar collector/storage system. Appl Energy 1981;8: 255–67.
[63] Underwood CP, Yik FWH. Modelling methods for energy in buildings. Oxford: Blackwell Science; 2004.
[64] Spencer DL, Strud RL. Integration of solar collector in large prefabricated roof/wall section. In: Proc. ISES Silver Jubilee Congress. 1979. p. 348–54.
[65] Bainbridge DA. Integral passive solar waters heater performance. In: Proc. ASME Sixth National Passive Solar Conf. 1979. p. 163–7.
[66] Sedgwick RHD, Patrick MA. The use of a ground solar collector for swimming pool heating. In: Proc. ISES Congress. 1981. p. 632–6.
[67] Olive G. Un nouveau capteur solaire en beton. Etudes Thermiques et Aerauliques 1977;8E(5):3–14.
[68] Turner RH. Concrete slabs as winter solar collectors. In: Proc. ASME Solar Energy Conference. 1986. p. 9–13.
[69] Turner RH. Concrete slabs as summer solar collectors. In: Proc. International Heat Transfer Conference. 1987. p. 683–9.
[70] Gao Q, Huang Y, Li M, Liu Y, Yan YY. Experimental study of slab solar collection on the hydronic system of road. Sol Energy 2010;84:2096–102.
[71] Wu S, Chen M, Zhang J. Laboratory investigation into thermal response of asphalt pavements as solar collector by investigation of small-scale slabs. Appl Therm Eng 2011;31:1582–7.
[72] Künzel H, Schwarz B, Fritzsche H-J. Experimentelle Untersuchungen über die Flächenleistung von Massivabsorbern. Holzkirchen: Fraunhofer-Institut für Bauphysik IBP; 1984.
[73] Schwarz B. Der Massivabsorber. Flüssigkeitsdurchströmte Betonbauteile als Flächenwärmetauscher und Wärmespeicher für Wärmepumpen-Heizungen. Holzkirchen: Fraunhofer-Institut für Bauphysik IBP; 1981.
[74] Künzel H, Schwarz B, Fritzsche H-J. Rechner-Simulationsprogramm für Massivabsorber-Wärmepumpenheizung. Holzkirchen: Fraunhofer-Institut für Bauphysik IBP; 1984.
[75] Al-Saad MA, Jubran BA, Abu-Faris NA. Development and testing of concrete solar collectors. Int J Sol Energy 1994;16:27–40.
[76] Jubran BA, Al-Saad MA, Abu-Faris NA. Computational evaluation of solar heating systems using concrete solar collectors. Energy Convers Manage 1994;35(12):1143–55.
[77] Hazami M, Kooli S, Lazâar M, Farhat A, Belghith A. Energetic and exergetic performances of an economical and available integrated solar storage collector based on concrete matrix. Energy Convers Manage 2010;51(6):1210–8.
[78] Hazami M, Kooli S, Lazâar M, Farhat A, Belghith A. Performance of a storage collector. Desalination 2005;183:167–72.
[79] Chaurasia PBL. Solar water heaters based on concrete collectors. Energy 2000;25:703–16.
[80] Tiwari GN. Solar energy. Fundamentals, Design, Modelling and Applications. New Delhi: Narosa; 2002.
[81] Farahat S, Sarhaddi F, Ajam H. Exergetic optimization of flat plate solar collectors. Renew Energy 2009;34:1169–74.
[82] Leonhardt H. Absorberdächer als Wärmequelle von Wärmepumpenheizungsanlagen. Holzkirchen: Fraunhofer-Institut für Bauphysik IBP; 1981.
[83] Oswald D. Wärmetechnische Untersuchungen an einer Wärmepumpenheizung mit massivem Dachabsorber und einem Erdkollektor. Stuttgart: Fraunhofer-Institut für Bauphysik IBP; 1983.
[84] Oswald D. Untersuchung einer Wärmepumpenheizung mit massivem Dachabsorber und Erdkollektor und ihrer Wirtschaftlichkeit. Stuttgart: Fraunhofer-Institut für Bauphysik; 1984.
[85] Primus I-F. An additional main pillar of business for precast plants. Massive absorbers–how concrete can promote climate protection. BTF Int 2010;76(11):38–45.
[86] Scheu W. Heizen mit Wärmepumpe und Beton. Wärmetechnik 1984;2:58–73.
[87] European Community Seventh Framework Programme. Cost-Effective. Resource- and Cost-effective integration of renewables in existing high-rise buildings. http://www.cost-effective-renewables.eu/.
[88] Ruschenburg J, Baisch K, Courtot F, Oltersdorf T, Herkel S. Experimental and simulation results on a solar-assisted heat pump prototype for decentral applications. In: Proc. 10th IEA Heat Pump Conference. 2011.
[89] Balocco C, Grazzini G, Rocchetti A. Una copertura come elemento attivo dell'impianto termico. In: Proc.: Convegno AiCARR Progettare l'involucro edilizio: correlazioni tra il sistema edificio e i sistemi impiantistici. 2001.
[90] Rocchetti A, Leoncini L. L'involucro edilizio attivo come sorgente per l'impianto a pompa di calore. In: Proc.: 66° Congresso Nazionale ATI. 2011.
[91] Rocchetti A, Leoncini L. Involucro attivo per la riqualificazione energetica degli edifici esistenti. In: Proc.: 48° Congresso Internazionale AiCARR. 2011.
[92] Miara M. Feldmessung neuer Wärmepumpen, Messergebnisse und Implikationen für den Neubau und den Gebäudebstand. In: Proc.: 8th GRE-Kongress. 2010.